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Agricultural Conversion Without External Water and Nutrient Inputs Reduces Terrestrial Vegetation Productivity

William Kolby Smith

University of Montana - Missoula

Cory C. Cleveland

The University of Montana, cory.cleveland@umontana.edu

Sasha C. Reed

Southwest Biological Science Center, Moab, Utah

Steven W. Running

University of Montana - Missoula, steven.running@umontana.edu

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RESEARCH LETTER

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Key Points:

- Globally, ~88% of agricultural lands are underproducing relative to the natural rates of NPP
- NPP reductions due to land cover conversion are greatest for tropical ecosystems
- Without new policies, agriculture will likely continue to degrade global NPP

Supporting Information:

- Readme
- Figures and Tables

Correspondence to:

W. K. Smith,
bill.smith@ntsg.umt.edu

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Agricultural conversion without external water and nutrient inputs reduces terrestrial vegetation productivity

W. Kolby Smith¹, Cory C. Cleveland², Sasha C. Reed³, and Steven W. Running¹
¹Numerical Terradynamic Simulation Group, Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, Montana, USA, ²Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, Montana, USA, ³Southwest Biological Science Center, U.S. Geological Survey, Moab, Utah, USA

Abstract Driven by global population and standard of living increases, humanity co-opts a growing share of the planet's natural resources resulting in many well-known environmental trade-offs. In this study, we explored the impact of agriculture on a resource fundamental to life on Earth: terrestrial vegetation growth (net primary production; NPP). We demonstrate that agricultural conversion has reduced terrestrial NPP by ~7.0%. Increases in NPP due to agricultural conversion were observed only in areas receiving external inputs (i.e., irrigation and/or fertilization). NPP reductions were found for ~88% of agricultural lands, with the largest reductions observed in areas formerly occupied by tropical forests and savannas (~71% and ~66% reductions, respectively). Without policies that explicitly consider the impact of agricultural conversion on primary production, future demand-driven increases in agricultural output will likely continue to drive net declines in global terrestrial productivity, with potential detrimental consequences for net ecosystem carbon storage and subsequent climate warming.

1. Introduction

Meeting future global food and bioenergy demands while mitigating the potential detrimental environmental impacts associated with industrialized agriculture has emerged as one of the greatest challenges facing humanity [Foley *et al.*, 2011; Tilman *et al.*, 2011]. As a result of continued population growth and increasing global meat consumption, global plant-derived food demand is expected to roughly double by 2050 [Tilman *et al.*, 2011; OECD/FAO, 2012]. Moreover, current energy forecasts predict multifold increases in bioenergy production in the near future, which will further drive demand for biomass and arable land [Scarlat and Dallemand, 2011; Smith *et al.*, 2012a, 2012b]. Two non-mutually exclusive options exist to meet this growing demand for agricultural products: (1) agricultural intensification—increased agricultural output per unit area of existing croplands and (2) agricultural extensification—increased agricultural output via the conversion of natural (i.e., nonagricultural, unmanaged lands) to agricultural land thereby increasing total cropland area. The capacity for these two options, either alone or in combination, to meet future demand is currently an area of intense scientific debate, anchored by well-justified concerns that agricultural intensity and extent may already be unsustainable in many regions [Galloway *et al.*, 2008; Rockström *et al.*, 2009, 2012; Running, 2012].

One key resource that faces severe degradation due to future agricultural expansion, yet has received surprisingly little consideration in the above debate, is terrestrial net primary productivity (NPP) [Running, 2012; Haberl *et al.*, 2013]. Terrestrial NPP represents the total annual growth of vegetation on land and is the basic resource upon which humanity depends for food, fiber, and, increasingly, energy [Vitousek *et al.*, 1986; Running, 2012; Krausmann *et al.*, 2013]. However, terrestrial NPP is also a major component of the global carbon (C) cycle, and a critical precursor to net ecosystem C storage, such that any change in NPP due to agricultural conversion could work to enhance or mitigate increasing atmospheric CO₂ concentrations and climate warming [Fargione *et al.*, 2008; Searchinger *et al.*, 2008]. At the local scale, agricultural conversion can either increase NPP (e.g., by management inputs that reduce biophysical growth limitations) or decrease NPP (e.g., by harvest-induced reductions in growing season length) [Long *et al.*, 2006]. Partially, as a result of these opposing potential impacts on NPP, the net effect of agricultural conversion on global-scale productivity remains relatively unresolved.

In this study we compared current agricultural NPP—derived from crop-specific yield and area agricultural statistics—with natural NPP—derived from satellite measurements of natural vegetation dynamics—to quantify the net impact of global-scale agricultural land cover conversion on the rates and overall magnitude of global terrestrial NPP (texts S1–S3 of the supporting information). Thus, unlike previous studies based solely on satellite data, we include areas where croplands are intermixed with natural vegetation at fine spatial scales, while we independently estimate rates of productivity for croplands and natural ecosystems in areas of codominance (text S4 of the supporting information). Next, we disaggregated our results by land cover conversion type, crop type, management intensity, and climate zone using a unique combination of the best available global data sets (text S4 of the supporting information). In quantifying the relative influence of these key factors, we attempt to identify strategies that, from a C balance perspective, should be avoided due to the potential for severe degradation of global terrestrial NPP and net ecosystem C storage.

2. Methods

We merged bottom-up, statistically derived estimates of agricultural NPP with top-down, satellite-derived estimates of natural NPP (texts S1–S4 and Figure S1 of the supporting information). Statistically based agricultural NPP was derived from two independent data sources that describe global agricultural area and yield by crop type [You *et al.*, 2006; Monfreda *et al.*, 2008]. Statistically derived agricultural data from the work of You *et al.* [2006] was available at 5 arc min (~8 km) spatial resolution for multiple crop types (20 staple crops) and previously disaggregated by management level (irrigated, high input, low input, and subsistence) according to spatially explicit irrigation and fertilization application data, which accounted for spatial heterogeneity in management efficiency (text S1 of the supporting information). Statistically derived agricultural data from the work of Monfreda *et al.* [2008] was available at 5 arc min (~8 km) resolution for all 127 non-tree crop types recognized by the Food and Agricultural Organization (FAO) of the United Nations (text S1 of the supporting information).

We converted agricultural yield data to NPP for both independent, statistically based data sources by applying crop-specific conversion factors (Table S1 of the supporting information). We then confirmed that there was a general agreement between our two estimates of agricultural NPP (texts S2 and S3 of the supporting information). We used 30 arc sec (~1 km) Moderate Resolution Imaging Spectroradiometer (MODIS) NPP data for both natural forest and natural non-forest land cover types to represent natural NPP, which we averaged over the 2000–2010 period and aggregated to a 5 arc min (~8 km) spatial resolution [Zhao *et al.*, 2005; Zhao and Running, 2010] (texts S2 and S3 of the supporting information). MODIS NPP was validated for both natural forests and natural non-forests against Ecosystem Model-Data Intercomparison NPP data, which consists of 5600 across-biome, ground-based observations of NPP, extrapolated globally using the National Center for Ecological Analysis and Synthesis regression model [Del Grosso *et al.*, 2008] (texts S2 and S3 of the supporting information). We then performed a cross-validation by comparing satellite-derived and statistically derived NPP estimates across regions dominated by agriculture lands and indeed found general agreement between the two estimates (text S3 of the supporting information). We used only the statistically derived estimates of agricultural NPP in the main analysis because these estimates consider only crop growth while satellite-derived estimates are biased by the inclusion of all vegetation growth, including non-crop growth [Lobell *et al.*, 2002; Hicke and Lobell, 2004] (text S3 of the supporting information).

We combined statistically derived and satellite-derived NPP estimates using a land cover classification that merged bottom-up fractional agricultural land cover data [Monfreda *et al.*, 2008] with top-down satellite land cover data [Friedl *et al.*, 2010] (text S4 of the supporting information). We then estimated the relative change in NPP (Δ NPP) due to agricultural conversion by comparing statistically based agricultural and satellite-based natural NPP estimates while accounting for the original (pre-agriculture) land cover type [Ramankutty and Foley, 1999] and controlling for climate zone [Peel, 2007] (text S5 of the supporting information). We further disaggregated Δ NPP by crop type, conversion type, management level, climate zone, and region and recursively related Δ NPP to the above stated predictor variables by applying a boosted regression tree and a standard classification and regression tree (CART) (text S6 of the supporting information). Finally, we constrained our results by decadal-scale interannual variability in natural NPP, estimated as the standard deviation of MODIS NPP recorded from 2000 through 2010 (text S6 of the supporting information).

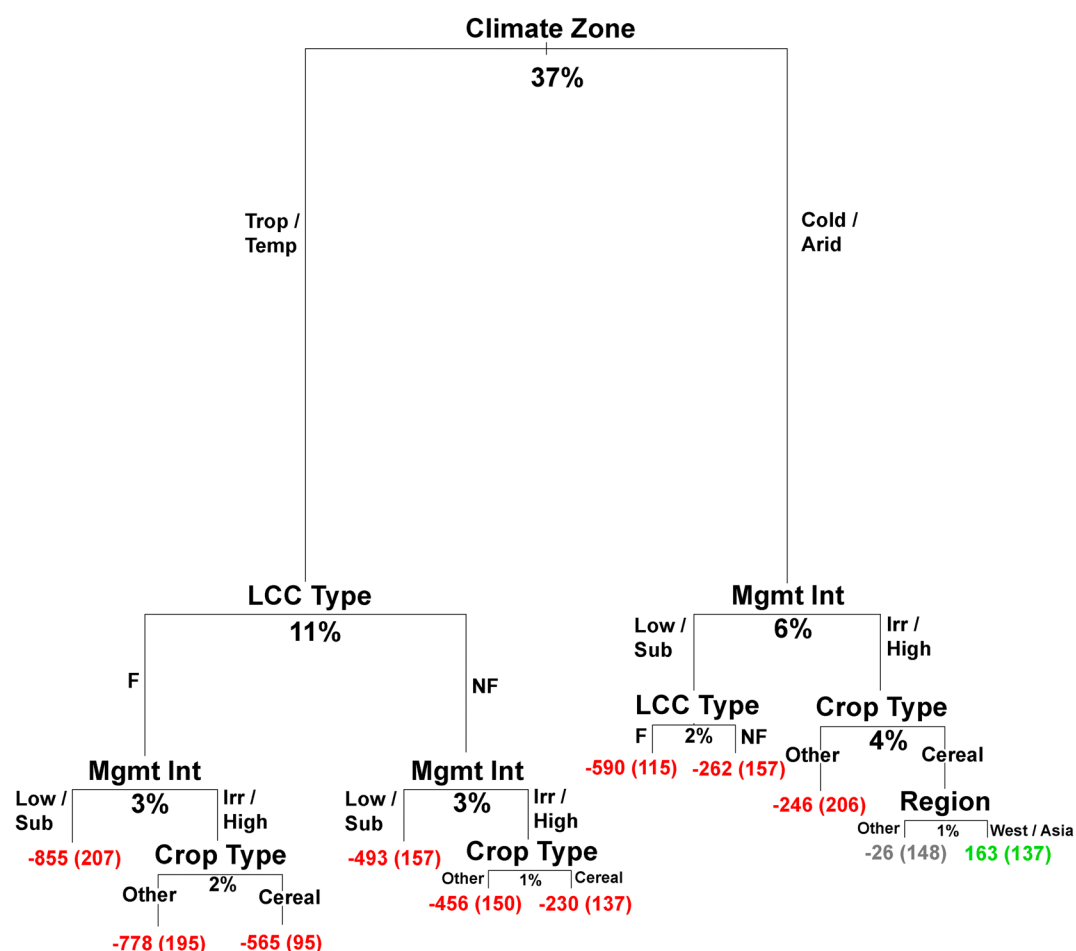


Figure 1. A regression tree showing the relative effect of key factors in determining the change in terrestrial primary production (Δ NPP) due to agricultural land cover conversion. (top) Predictor variables and (bottom) the mean Δ NPP (with decadal-scale natural variability in parentheses). Mean Δ NPP values that represent a significant decrease, a nonsignificant change, or a significant increase relative to decadal-scale natural variability at a significance level of < 0.001 are colored coded red, gray, and green, respectively. The height of each branch, as well as the percentage value below each branch, indicates the relative proportion of the total sum of squares explained. Abbreviations: Trop: tropical; LCC: land cover conversion; Mgmt Int: management intensity; Sub: subsistence; Irr: irrigated; F: forest; NF: non-forest; West: industrialized West.

3. Results and Discussion

Our analysis indicates that the conversion of natural ecosystems to agricultural systems has significantly reduced global terrestrial NPP (Δ NPP) well outside the range of natural variability (Figures 1 and 2). We estimate a net reduction in terrestrial NPP of $3.0 \pm 0.68 \text{ Pg C y}^{-1}$ for 20 staple crops, which together comprise nearly 90% of agricultural land globally (Figure 2 and Table S2 of the supporting information). When considering all 127 non-tree crops recognized by the Food and Agricultural Organization of the United Nations, the reduction in NPP increased to $3.7 \pm 0.85 \text{ Pg C y}^{-1}$, equivalent to an $\sim 7.0\%$ reduction in terrestrial NPP (Table S3 of the supporting information). These results are relative to current satellite-derived rates of global terrestrial NPP (53.1 Pg C y^{-1}), which represent the lower end of current published estimates across measurement methods (range: $59.5 \pm 8.9 \text{ Pg C y}^{-1}$) [Ito, 2011]. Thus, our estimate of the total reduction in NPP due to agricultural conversion is likely conservative.

Our results suggest that $\sim 88\%$ of agricultural systems are underproducing relative to the natural productivity potential of the land, while $\sim 12\%$ of agricultural lands have increased productivity relative to the natural potential (Figures 1 and 2). This variability in Δ NPP—ranging from positive (i.e., an increase in NPP due to agricultural conversion) to negative (i.e., a decrease in NPP due to agricultural conversion)—can be explained by a few key drivers (Figure 1 and Tables S2–S3 of the supporting information). Climate was clearly a major

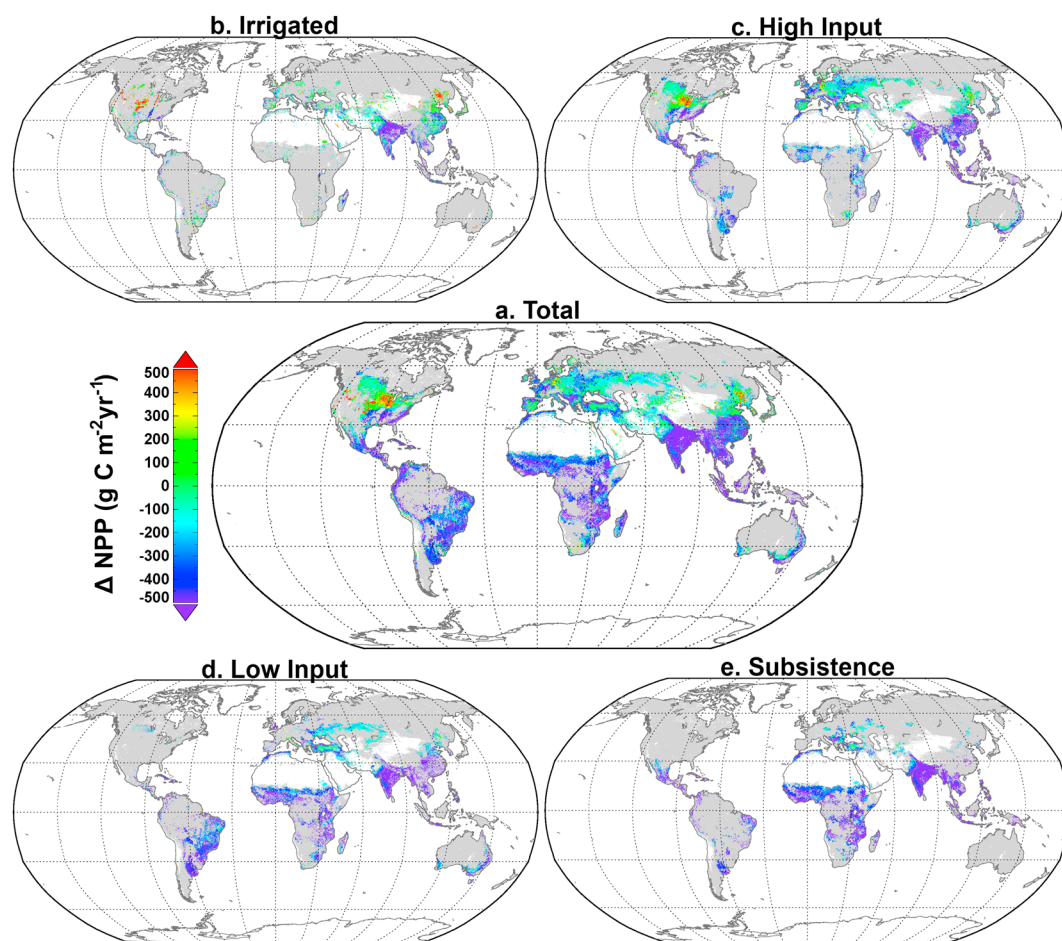


Figure 2. Spatially explicit estimate of the effect of agricultural land cover conversion on terrestrial primary production for 20 staple crops. The change in terrestrial primary production (ΔNPP) due to agricultural land cover conversion was estimated for (a) total, (b) irrigated, (c) high input, (d) low input, and (e) subsistence agricultural lands. All remaining vegetated land is represented in gray, while water and barren areas are represented in white. For these 20 staple crops, we estimate that agricultural land cover conversion has reduced terrestrial NPP by $\sim 5.7\%$ with agricultural lands under irrigated, high input, low input, and subsistence management strategies reducing NPP by $\sim 1.0\%$, $\sim 1.6\%$, $\sim 1.7\%$, and $\sim 1.4\%$, respectively (Table S2 of the supporting information). Across all 127 FAO recognized non-tree crop types (not shown), we estimate an $\sim 7.0\%$ reduction in terrestrial NPP due to agricultural conversion (Table S3 of the supporting information).

determinant of ΔNPP : Climate zone was identified as the top branch in the regression tree (CART) analysis, explaining 37% of the sum of square variance in ΔNPP (Figure 1 and text S6 of the supporting information). For tropical and temperate climate zones, mean ΔNPP was always negative, indicating a consistent reduction in NPP due to agricultural conversion. This reduction was independent of conversion type, management intensity, crop type, or region, although these factors did mitigate the reduction in productivity to various degrees (Figure 1). This finding emphasizes the high productivity of natural ecosystems relative to agricultural ecosystems, particularly in tropical forests and savannas ($\sim 71\%$ and $\sim 66\%$ average reductions in NPP due to agricultural conversion, respectively; Figure 1 and Figure S6 of the supporting information). Previous research supports this finding and has identified disproportionately detrimental impacts in terms of reductions in productivity [Field, 2001; DeFries, 2002], biodiversity [Foley et al., 2005; Thomas et al., 2012], and C stocks [West et al., 2010; Oliveira et al., 2013] as a result of the conversion of tropical and temperate ecosystems to agricultural land.

For cold and arid climate zones, ΔNPP varied from positive to negative, although the overall net effect of agricultural conversion on NPP was strongly negative (Figure 1). Mean positive ΔNPP was only observed for cereal crops grown in the industrialized West and Asia under relatively intensive management (i.e., either irrigated or rainfed with high fertilizer inputs), confirming that intensive management can increase the

productivity of agricultural systems relative to their natural counterparts, and also indicating that natural NPP is generally higher than agricultural NPP under natural nutrient and biophysical growth constraints (Figure 1 and Figure S6 of the supporting information). The increasing importance of management intensity in these climate zones likely reflects the increasing potential for irrigation and fertilization to mitigate biophysical water and nutrient constraints, respectively [Johnston *et al.*, 2011; Mueller *et al.*, 2012]. Although less important than management, cereal crops were consistently grouped separately (Figure 1), indicating that cereals most closely match natural rates of NPP across climate zones. This is consistent with research suggesting that cereals are near their theoretical yield potential ceiling due to over 30 years of research and development of improved cultivars [Cassman, 1999; Zhu *et al.*, 2010]. Further, relative to other crop types such as energy dense oil crops, cereal crops more closely match the C allocation strategy of the natural vegetation, which could contribute to higher rates of productivity that more closely match those of the natural vegetation [Gelfand *et al.*, 2013]. Finally, we show that much of the world (Latin America, Africa, the Middle East, and Eastern Europe) is underproducing relative to the industrialized West and Asia (Figure 1 and Figure S3 of the supporting information), suggesting that increases in agricultural output could be achieved without increasing management inputs and resource consumption, but instead by a more even global distribution of technology and advanced management practices [Licker *et al.*, 2010; Foley *et al.*, 2011; Mueller *et al.*, 2012].

Considering only the dominant agricultural climate zones and controlling for the top predictor variables (conversion type and management intensity), we further elucidate the link between positive Δ NPP values and management intensity (Figure 2 and Figure S6 of the supporting information). Again, in biophysically constrained climate zones (i.e., cold and arid climates), positive mean Δ NPP values were realized only in intensively managed systems (i.e., irrigated and/or high fertilizer input) (Figure 2 and Figure S6 of the supporting information). Yet, these gains over natural rates of productivity have come at a cost. For example, the global depletion of groundwater has more than doubled from 1960 to 2000, mainly due to increased rates of irrigation [Wada *et al.*, 2010]. Similarly, current fertilization rates have been linked to extensive eutrophication of freshwater and coastal zones, along with increased emission of the potent greenhouse gas nitrous oxide (N_2O) [Crutzen *et al.*, 2008]. Thus, future policy should continue to promote improved resource use efficiency on agricultural lands [Vitousek *et al.*, 2009; Mueller *et al.*, 2012]. As a first step, the monitoring of soil moisture and nutrient quality on current intensively managed agricultural lands could help to prevent excessive water and nutrient inputs. In the case of nutrient additions, research suggests that, in specific regions, this relatively small monitoring effort could reduce nutrient losses by greater than 50% without detrimentally impacting yields or soil quality [Ju *et al.*, 2009].

The results of this analysis also have important implications for global bioenergy production and challenge the long-standing assumption that bioenergy crops are C neutral. The C neutrality assumption posits that C released during biomass combustion was previously absorbed during biomass growth and thus ultimately has a net neutral impact on the atmospheric C pool [DeCicco, 2013; Haberl, 2013]. Yet, this assumption ignores the impact of land use change on the exchange of C between the atmosphere and the biosphere [Fargione *et al.*, 2008; DeCicco, 2013; Haberl, 2013]. Our data suggest that many of the major first generation bioenergy crops (e.g., cereal crops, oil crops, and sugar crops) could significantly reduce terrestrial vegetation productivity, thus, reducing the flow of C from the atmosphere to the biosphere (Figure 1 and Figure S4 of the supporting information). By contrast, some second generation bioenergy crops (e.g., C_4 perennial grasses) that more closely match the C allocation strategy and quality of the natural vegetation have the potential to minimize this C trade-off, however, the conversion of lower quality biomass to usable energy has yet to be demonstrated as economically viable at the large scale [Gelfand *et al.*, 2013]. Irrespective of the technology, ignoring the change in NPP due to agricultural conversion could result in flawed estimates of the C offset potential of bioenergy, which, particularly in the case of first generation bioenergy crops, could drive an unaccounted for increase in annual greenhouse gas emissions [Fargione *et al.*, 2008; DeCicco, 2013; Haberl, 2013].

While the impact of human land use on atmospheric CO_2 concentrations has remained relatively constant for at least the last 50 years [Le Quéré *et al.*, 2009; Ballantyne *et al.*, 2012], demand-based projections indicate that future agricultural expansion is likely unavoidable [Tilman *et al.*, 2011; Ray *et al.*, 2013], with disproportionately large increases in the agricultural conversion of temperate and tropical biomes [DeFries, 2002; West *et al.*, 2010]. Concurrently, research suggests that net global C storage—regulated in part by vegetation productivity—has been steadily increasing for at least the last 50 years, such that 55% of the total CO_2 emitted by humans to the

atmosphere has moved into biospheric sinks, thus, significantly reducing the rate of climate warming [Ballantyne *et al.*, 2012]. The exact locations and mechanisms responsible for increased global C uptake remain uncertain, however, the tropics and temperate biomes have been identified as regions with a high potential capacity for additional C storage [Pan *et al.*, 2011; Cleveland *et al.*, 2013]. Our results indicate that agricultural expansion into these highly productive biomes would likely be accompanied by significant declines in NPP, in turn, reducing the strength of the terrestrial C sink. Future policies aimed at addressing the many socioeconomic drivers of agricultural conversion—particularly within tropical biomes—may help stem continued declines in global terrestrial NPP.

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